

Cognitive task effects on gait stability following concussion

Robert D. Catena · Paul van Donkelaar ·
Li-Shan Chou

Received: 15 September 2005 / Accepted: 10 June 2006 / Published online: 7 July 2006
© Springer-Verlag 2006

Abstract The purpose of this study was to determine how two different types of concurrent tasks affect gait stability in patients with concussion and how balance is maintained. Fourteen individuals suffering from a grade II concussion and 14 matched controls performed a single task of level walking and two types of concurrent tasks during level walking: a discrete reaction time task and a continuous sequential question and answer task. Common gait spatial/temporal measurements, whole-body center of mass motion, and the center of pressure trajectory were recorded. Concussed individuals demonstrated differences in gait while performing single-task level walking and while being challenged with a more difficult secondary task compared to normal controls. Concussed individuals adopted a slower, more conservative gait strategy to maintain stability, but still exhibited signs of instability with center of mass deviations in the coronal plane increasing by 13% during the question and answer dual-task and 26% more than control subjects. Trends of attentional deficits were present with the question and answer task, while the reaction time task seemed to help concussed individuals be more alert to their gait and stability. Recommendations for a sensitive testing protocol of deficits following concussion are explained.

Keywords Concussion · Cognition · Dual-task · Attention · Gait

Introduction

Commonly reported symptoms of a concussion include cognitive (i.e. concentration, memory, attention and judgment) deficits and movement (i.e. strength, coordination and balance) disabilities (Thurman et al. 1999). These symptoms have been known to last even up to a year in mild cases of concussion (Bernstein 2002). Increased neurological susceptibility to a second concussion has also been noted (Guskiewicz et al. 2000). During this period of time, subsequent concussions can lead to permanent brain damage (CDC 1997). However, removal from activity and rest for a severity-determined amount of time is currently the most utilized treatment after a concussion (Brukner and Kahn 2001). The areas of deficits mentioned above are broad areas of human neurological functioning. If symptoms of concussion that may directly result in another concussion (i.e., instability and attentional deficits) can be detected and tracked, we can then begin the process of accurately identifying the presence of residual symptoms, thereby avoiding subsequent concussions that can lead to more permanent damage.

Two of the residual symptoms frequently complained about by severely brain injured patients, coordination deficits and imbalance during gait, have been previously assessed using gait spatial/temporal parameters (McFadyen et al. 2003). More recently, measurements of center of mass (CoM) trajectory were reported to provide a more accurate description of how the body moves in space and also provide insight into

R. D. Catena · L.-S. Chou (✉)
Motion Analysis Laboratory,
Department of Human Physiology,
1240 University of Oregon, Eugene,
OR 97403, USA
e-mail: chou@uoregon.edu

P. van Donkelaar
Eye Hand Laboratory, Department of Human Physiology,
University of Oregon, Eugene, OR 97403, USA

dynamic balance control mechanisms during locomotion (Vallis and Patla 2004). Studies on patients after a mild or moderate/severe traumatic brain injury (TBI) have confirmed that CoM motion and its interaction with the center of pressure (CoP) during gait are able to better identify conservative gait adaptations and quantify gait instability (Chou et al. 2004; Parker et al. 2005). All patients displayed gait instability marked by significant increases in coronal plane CoM motion. While gait instability might be a common complaint after a severe TBI, individuals inflicted with a concussion rarely complain or report instability. Krauss et al. (1997) have shown self-reported incidence levels of movement disorders following mild TBI (mTBI) to be low, but other reports measuring balance conflict with these self-reports. A group of predominately mTBI subjects displayed deficits in finger tapping even up to a year post-injury (Haaland et al. 1994). Children with mTBI display balance deficits up to 12 weeks post-injury (Gagnon et al. 2004). Parker et al. (2005) show instability in college-aged adults following a mild concussion as well.

Cognitive tests have been incorporated with gait to provide dynamic attentional tests in a dual-task setting (Bardy and Laurent 1991; Lajoie et al. 1993; Ebersbach et al. 1995; Weerdesteyn et al. 2003). Cognitive/motor dual-task situations have been described as most similar to real life scenarios (Cock et al. 2003; Weerdesteyn et al. 2003; Parker et al. 2005). Earlier studies were more inclined to use a simpler secondary task to perturb gait stability, such as a simple reaction time test (Bardy and Laurent 1991; Lajoie et al. 1993). Recently, researchers have used more complex secondary tasks such as backwards digit-span (Ebersbach et al. 1995) and auditory Stroop tests (Weerdesteyn et al. 2003) to see effects not only in the secondary task, but also in gait.

The combination of motor disabilities and cognitive deficits increase a concussed individual's vulnerability to gait instability and subsequent concussions. Current research using a secondary task during gait in a concussed population is limited, not only in quantity, but also in scope. Only limited information is available describing divided attention of concussed subjects with a single type of secondary task (Chou et al. 2004; Parker et al. 2005). Examining motor function on a battery of dual-task situations is essential to identifying the underlying mechanism for reduced performance during dual tasks due to brain injuries (Haggard et al. 2000). Researchers have yet to examine the difference in gait stability between a simpler and a more complex secondary task in a concussed population.

The purpose of this study was to examine whether two commonly utilized attentional tests, the simple

reaction time (RT) and the question and answer (Q&A) task, would impose different effects on gait stability in a group of concussed individuals compared to matched controls. Specifically we aimed to: (1) detect differences in gait stability between a group of college-aged subjects with concussions and age-matched controls; and (2) detect differences in gait stability between dual-task scenarios of varying difficulty. More perturbed gait stability was hypothesized to result from the more difficult dual-task scenario. Concussed individuals were hypothesized to exhibit a more conservative gait strategy during single-task walking, with possible instability and decreased secondary task performance during dynamic attentional tests. Results from this study will hopefully shed some light on balance control after a concussion for future implementation of detection protocols measuring residual symptoms in a clinical setting.

Materials and methods

Participants

Approval for the use of human subjects was granted prior to testing by the University of Oregon Institutional Review Board. Written and verbal instructions of testing procedures were provided, and written consent was obtained from each subject prior to testing. Twenty-eight college-aged adults participated in this study. All subjects were recruited from the University of Oregon student body and had obtained a similar level of education. Subjects were divided into two groups: 14 subjects suffering from concussion (CONCs) and 14 controls without injury (NORMs).

CONCs (6 females/8 males; age = 22.29 ± 4.46 years; mass = 75.24 ± 15.36 kg; height = 173.41 ± 8.47 cm) were diagnosed with grade II concussions as defined by the American Academy of Neurology Practice Parameters (American Academy of Neurology 1997). Under these guidelines, a grade II concussion entails transient confusion, and symptoms lasting longer than 15 min, but no loss of consciousness. Exclusion criteria included a concussion within the year preceding the most recent concussion, preexisting injury or surgery that affects normal gait patterns, or preexisting injury or surgery that affects normal cognitive abilities. Five of the CONCs had previously been inflicted with a concussion more than two years prior to the most recent concussion.

NORMs were matched by gender (6 females and 8 males), age (22.29 ± 3.05 years), mass (75.07 ± 16.93 kg), and height (172.82 ± 8.50 cm). The matching

of CONCs and NORMs allowed for the groups to be comparable without normalization. Exclusion criteria of NORM subjects were the same as the exclusion criteria for CONC subjects, with the additional exclusion criterion of exhibiting common symptoms of concussion (e.g. vision problems, nausea, headaches, etc.) described by Collins et al. (1999). Similarly, five of the NORMs had previously been inflicted with a concussion more than two years prior to their participation in this study, but none complained of any lingering effects.

Experimental apparatus

All data were collected in the Motion Analysis Laboratory of the University of Oregon. Twenty-nine retroreflective markers were attached to anatomical landmarks, modified from a previously validated marker setup (Hahn and Chou 2004). Three-dimensional marker trajectories in space were collected by eight Eagle digital cameras using Expert Vision Real Time (EVaRT) version 4.37A motion tracking system (MotionAnalysis, Santa Rosa, CA). The cameras were positioned surrounding an 8-m walkway. Ground reaction forces in three orthogonal directions and moments about the three axes were collected by two in-series strain gauge force plates (Advanced Mechanical Technologies Inc. Watertown, MA), flush with the top surface of the floor in the center of the walkway.

During RT tests, a radio telemetry handheld trigger (TS0611T, Isaacs & Associates Inc., Walla Walla, WA) was used to signal a response. An infrared photocell (RadioShack, Fort Worth Tx) was set up so that the beam passed between the two force plates. This was used to create an audible cue to which the subjects had to respond. If set to “on”, an easily discernible beep occurred. The sound operating system was set up so that the subject could not tell if a sound would occur until the photocell beam was broken. The beam was set up so that the cue would sound just prior to the foot contact with the second force plate.

Experimental protocol

Testing of CONC subjects occurred within 48 h post-injury (37.36 ± 12.41 h). Data collection started with a single-task session (LEVEL). Subjects were asked to perform barefooted level walking at a comfortable self-selected pace. The gait initiating foot was not regulated. Rather, subjects were told to proceed with gait throughout the testing “as normal and comfortable as possible.” Several practice trials were allowed so that subjects could become comfortable walking with the

marker set and the starting spot could be adjusted by the proctor to insure that subjects hit each force plate with the entire foot. Subjects were not informed as to the reason for position adjustment so that conscious adjustments in gait could be avoided.

The first dual-task situation Q&A required level walking with a question and continuous answers task. Questions included common tests from a clinical mental status examination: spelling a common five-letter word in reverse, continuous subtraction by a certain number, and reciting the months of the year in reverse order (Bell and Hall 1977). The order and specifics of each task were not shared with the subject prior to testing. Only at the beginning of each trial was the subject given the specific task for that trial (e.g. count backwards by sevens starting at 93, or months of the year in reverse starting at February). The subject then started walking and answering at the same time and stopped answering when the end of the walkway was reached. Only the first five responses (not including corrections) were recorded so that starting position and gait velocity did not factor into the number of answer attempts. Once at the end of the walkway, subject responses were no longer recorded.

The second dual-task situation was a RT test during level walking. Subjects would hear an audible cue when the photocell beam was broken and then respond by pressing a button on the handheld trigger. Subjects were given instructions to react as soon as possible taking into consideration that catch trials (trials without a cue) were randomly dispersed throughout the testing session. Approximately 50% of the trials in this section were catch trials so that subjects were unaware of when a cue would occur. Prior to testing, the subjects were allowed to hear the audible cue, and told the approximate location where the sound could occur to relieve the possibility of a learning effect during the entire experiment. Baseline static reaction times (SRT) were collected before and after the dynamic RT trials. During the SRT trials, the subject stood off to the side while a proctor walked through the walkway and initiated the breaking of the photocell beam and subsequent sound. Catch trials were randomly dispersed throughout the static sessions as well so that subjects were unaware of when a cue would occur. The subject stood behind and to the right of the starting position so that there was a clear view of when the proctor was crossing over the previously indicated position of beam breakage. This was most similar to dynamic RT trials, but without the subject performing any dynamic motor task.

Each walking trial lasted approximately 8 s. The subject then returned to the starting position and waited several seconds for the next trial to begin. Subjects rested for several minutes twice during the testing session during each transition to a new testing condition. Each subject performed approximately 60 trials.

Data processing

The analog signals from the photocell, radio telemetry receiver and the two force plates were collected at 960 Hz for 4 s. EVaRT 4.37A (MotionAnalysis, Santa Rosa, CA) was used to track the markers in space for 4 s at 60 Hz. The marker trajectories were filtered with a low-pass fourth order Butterworth filter at a cutoff frequency of 8 Hz. Kinematic data were used to locate the CoM of 13 different segments: head, trunk, two upper arms, two lower arms, pelvis, two thighs, two shanks, and two feet. Calculations for the CoM locations were based on Dempster's (Winter 1990) anthropometric data. A weighted sum method was used to calculate the whole body CoM from each segment CoM during each time point. CoM data were truncated from the first heel strike on to the first force plate to the heel strike of the same foot after the second force plate, and individual gait events were identified for further processing. CoM velocities were estimated with the use of Woltring's generalized cross-validated spline algorithm for determining first and second derivatives (Woltring 1986). CoP data were calculated for all time points that the subject was in contact with a force plate, and not the lab floor. Laboratory written programs (Motion Analysis Lab, University of Oregon) in Matlab 7.0 (Mathworks Inc., Natick, MA) were used to complete the processing of the data during one complete stride.

The CoM sagittal plane range of motion (AP ROM), the coronal plane range of motion (ML ROM), and the peak velocities in the A/P (AP V) and M/L directions (ML V) were recorded. The CoM data were synchronized with the CoP data to find the maximum horizontal separation distance between the CoM and CoP in both the sagittal plane (APmax) and coronal plane (MLmax) (Fig. 1). Common spatial-temporal gait parameters were also calculated during the entire stride: gait velocity, stride length, average step width, and stride time.

Reaction time was calculated from the time difference between the photocell signal onset and trigger signal onset. The number of answers attempted, and the number of answers correct were recorded during each Q&A trial by a proctol. The ratio of answers correct

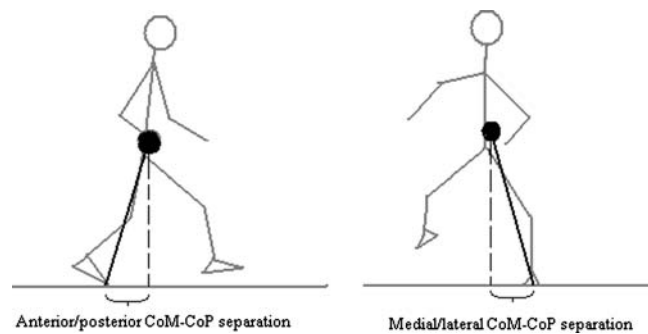


Fig. 1 Profiles of the maximum horizontal separation distance between the CoM and the CoP in both the anterior/posterior (APmax) direction and medial/lateral direction (MLmax) as indicated by the brackets at the bottom. The relationship between the CoM and CoP is modeled as an inverted pendulum with instability in the system as separation distance increases

divided by answers attempted (answer percentage) was calculated later during processing.

Data analysis

The group by task interactions, the differences between task conditions and the differences between groups were statistically examined with SPSS 12.0 (SPSS Inc., Chicago, IL). Two-way (2 groups, 3 tasks) ANOVAs with repeated measures were used to determine group-by-task interactions for primary (gait) task variables ($P < 0.05$). If significance was determined, then a Bonferroni pairwise comparison was used to determine between which specific tasks in each group. If significance was not present for group-by-task interactions, main effects between groups and between tasks were examined. If significance was present between group means ($P < 0.05$), a Tukey's honestly significant difference post-hoc analysis was conducted to determine between groups, within task, significant effects. If significance was present between task means ($P < 0.05$), a Bonferroni pairwise comparison was used to determine which tasks were statistically different.

Answers attempted, answers correct and correct percentage in the Q&A task were examined for group differences with independent sample *t*-tests ($P < 0.05$). Subject demographics of each group were compared with independent sample *t*-tests as well ($P < 0.05$). Two-way (2 groups, 4 tasks) ANOVAs with repeated measures were used to determine group by task interactions for RT variables ($P < 0.05$). There were two groups (CONC and NORM) and four task conditions: dynamic RT, average SRT, SRT before RT and SRT after RT.

Results

Spatial–temporal gait parameters

The analysis of gait spatial-temporal parameters indicated both group and task differences, but no group-by-task interactions (Table 1). CONCs walked significantly slower than NORMs during all tasks ($F_{1,26} = 8.583$, $P = 0.007$). Both groups walked significantly slower during Q&A as compared to LEVEL ($F_{2,52} = 29.038$, $P < 0.001$) and to RT ($F_{2,52} = 29.038$, $P < 0.001$). CONCs took a significantly longer amount of time than NORMs to complete a stride ($F_{1,26} = 6.121$, $P = 0.020$). All subjects took longer to complete a stride during Q&A as compared to RT ($F_{2,52} = 9.432$, $P < 0.001$). Significant decreases in stride length and significant increases in step width were exhibited during Q&A when compared to RT ($F_{2,52} = 7.038$, $P = 0.003$ and $P < 0.001$, respectively).

Sagittal plane CoM motion

Significant decreases in AP ROM and APmax were only detected in both groups during the Q&A task when compared to LEVEL ($F_{2,52} = 8.883$, $P = 0.020$ and $F_{2,52} = 6.478$, $P = 0.032$, respectively) and to RT ($F_{2,52} = 8.883$, $P = 0.003$ and $F_{2,52} = 6.478$, $P = 0.014$, respectively) (Table 2). These changes corresponded with decreases in the stride length during Q&A. Likewise, the change in AP V was similar to the changes seen in gait velocity. CONCs had a significantly slower peak AP velocity than NORMs during all tasks ($F_{1,26} = 8.536$, $P = 0.007$).

Coronal plane CoM motion

Side to side CoM sway (ML ROM) during a stride was significantly greater in CONCs than in NORMs for LEVEL and Q&A ($F_{1,26} = 4.630$, $P = 0.041$) (Table 3). Peak CoM sway velocity (ML V) was also significantly greater in CONCs than in NORMs for LEVEL and Q&A ($F_{1,26} = 4.401$, $P = 0.046$). Both groups swayed significantly faster during Q&A compared to RT ($F_{2,52} = 3.496$, $P = 0.032$).

Secondary task performance

Neither significant group nor significant task differences were detected for RT measurements (Table 4). Both groups demonstrated similar RTs for each task (ranging from 340 to 410 ms). The concussed group displayed a large amount of inter-subject variability in their RTs as compared to the control group and compared to intra-subject variability. Neither group responded with significantly more answers correct or with a significantly better answer percentage during the Q&A task (Table 4). However, CONCs showed a trend of attempting fewer answers than NORMs ($P = 0.085$).

Discussion

Our goal was to distinguish a dynamic dual-task scenario that could effectively demonstrate the presence of residual deficits in a concussed population. Identification of an appropriate secondary task will enhance

Table 1 Mean values and standard deviations of all spatial/temporal variables analyzed for both groups during each task

	Conc			Norm		
	Level	RT	Q&A	Level	RT	Q&A
Gait velocity (m/s)	1.219 (0.137) α	1.245 (0.157) α	1.097 (0.166) ** α	1.361 (0.136)	1.369 (0.132)	1.276 (0.133) **
Stride time (s)	1.110 (0.139) β	1.069 (0.109)	1.189 (0.148) $\dagger\beta$	1.036 (0.062)	1.023 (0.060)	1.060 (0.075) \dagger
Stride length (m)	1.311 (0.129)	1.330 (0.120)	1.285 (0.125) *	1.404 (0.100)	1.395 (0.102)	1.346 (0.109) *
Step width (m)	0.112 (0.029)	0.101 (0.022)	0.113 (0.021) \dagger	0.094 (0.035)	0.087 (0.031)	0.093 (0.032) \dagger

* Significantly less than RT., ** Significantly less than LEVEL and RT., \dagger Significantly greater than RT., α Significantly less than NORM., β Significantly greater than NORM

Table 2 Mean values and standard deviations of all sagittal plane variables analyzed for both groups during each task

	Conc			Norm		
	Level	RT	Q&A	Level	RT	Q&A
AP ROM (m)	1.321 (0.130)	1.333 (0.122)	1.288 (0.126) **	1.409 (0.100)	1.400 (0.102)	1.348 (0.105) **
AP V (m/s)	1.373 (0.165) α	1.376 (0.161) α	1.234 (0.168) ** α	1.523 (0.157)	1.535 (0.154)	1.427 (0.154) **
APmax (m)	0.204 (0.036)	0.204 (0.035)	0.189 (0.041) **	0.225 (0.022)	0.222 (0.026)	0.214 (0.028) **

** Significantly less than LEVEL and RT., α Significantly less than NORM

Table 3 Mean values and standard deviations of all coronal plane variables analyzed for both groups during each task

	Conc			Norm		
	Level	RT	Q&A	Level	RT	Q&A
ML ROM (m)	0.038 (0.006) β	0.038 (0.007)	0.043 (0.010) β	0.033 (0.009)	0.035 (0.012)	0.034 (0.010)
ML V (m/s)	0.142 (0.016) β	0.134 (0.022)	0.149 (0.020) $\dagger\beta$	0.119 (0.037)	0.117 (0.037)	0.122 (0.039) \dagger
MLmax (m)	0.081 (0.026)	0.075 (0.015)	0.078 (0.020)	0.071 (0.023)	0.071 (0.020)	0.074 (0.020)

\dagger Significantly greater than RT., β Significantly greater than NORM

Table 4 Mean values and standard deviations of all secondary task variables analyzed for both groups

	Conc	Norm	<i>P</i> -values
Static RT (s)	0.395 (0.186)	0.349 (0.120)	0.442
Dynamic RT (s)	0.381 (0.207)	0.384 (0.096)	0.966
Answers correct	3.719 (0.940)	4.075 (0.733)	0.274
Answers attempted	4.023 (0.642)	4.450 (0.621)	0.085
Answer percentage	0.895 (0.166)	0.902 (0.090)	0.899

the ability of detecting deficits in dynamic motor functions and then begin the process of defining a much needed testing protocol for concussed individuals.

Effects of concussion on gait

Effects of concussion on gait are illustrated by differences between subject groups in both single-task and dual-task scenarios. Changes in spatial-temporal gait parameters have been previously described as a sign of conservative gait adaptations in an elderly population with a fear of falling (Maki 1997). Significant decreases in gait velocity and peak anterior CoM velocity for CONCs suggest a conservative gait strategy, similar to the findings of Chou et al. (2004) and Parker et al. (2005). These changes are thought to be an effort to reduce the CoM forward momentum during gait progression (Kaya et al. 1998; Hahn and Chou 2004) and may indicate a degraded ability to maintain gait stability in individuals suffering from a concussion. Whether these changes are inherent, or conscious adjustments made by the individual, can only be revealed with further surveying.

Coronal plane CoM motion was previously used to indicate gait instability (Chou et al. 2003, 2004). The current study demonstrated that subjects with a grade II concussion displayed a significantly faster CoM velocity as well as a significantly greater CoM sway in the coronal plane during single and dual-tasks. Changes in coronal plane CoM motion are thought to possibly be due to a reduced ability to confine the CoM within a more stable region. Our results are comparable to those observed in a balance impaired group

(Chou et al. 2003) and a severe TBI group complaining of dizziness and unsteadiness during walking (Chou et al. 2004). Increased medial/lateral motion can directly result in sideways falls for which there are reduced safety mechanisms: reduced vision to the side, only one arm to aid in fall deceleration and reduced leg motion to stop a fall. It has been reported that TBI could also lead to reductions in strength (Thurman et al. 1999) and coordination (Slobounov et al. 2002). Reduced strength would diminish the body's ability to counteract the larger moment from the body weight when the CoM moves near the edges of the base of support; specifically with an inability to produce greater torques at supporting joints. Reduced coordination could adversely affect the timing of muscle contractions around supporting joints. Another possibility is that visual inputs may be affected in our group of concussed individuals. Even though vision problems were not mentioned by our subjects, Collins et al. (1999) have described vision problems following concussions, and no formal data was collected for our subjects.

Dual-task difficulty

Lajoie et al. (1993) and Brown et al. (1999) previously confirmed that balance performance simultaneously decreases as dual-task difficulty increases. In the current study, the level of difficulty of dual-task scenarios was compared and determined by the impact each had on common measurements of gait. Conceptually and experimentally, the continuous Q&A secondary-task is more difficult than the discrete RT secondary-task.

The Q&A task resulted in a more conservative gait in all subjects. The continuous Q&A secondary task affected sagittal plane gait measures when examining all subjects together. Subjects decreased their gait velocity by a combination of increased stride times and decreased stride lengths. These changes were adopted to reduce the CoM's forward momentum (i.e., the anterior velocity) and to shorten the horizontal separation distance between the CoM and CoP.

In contrast to the Q&A task, we found that the simple RT secondary task did not affect any gait measures compared to level walking. This could be due to the fact that the RT task was only performed once near the middle of the walkway, while the Q&A task required continual responses throughout the trial. An additional possibility is that simple RT response formation was not difficult enough, unlike the Q&A task. The effects of fatigue over the testing session were ruled out as a contributing factor towards inter-condition differences with an examination of level walking at the beginning and end of the testing session, which showed no significant differences.

Attentional deficits after concussion

All participants had similar dynamic and static RTs in the current study. Although differences were expected, we suspect that design simplicity was a contributing factor. Previous studies have administered a continuous RT test starting at or soon after gait initiation. A high degree of response variability has been associated with discrete tests (de Jong 1995), similar to our findings for RT. The particularly high RT variability exhibited by the concussed group is believed to be a result of inter-subject difference in concussive episodes. Although matched by the grade of concussion, the levels of grading used were highly unspecific, each encompassing a wide range of severity. Higher sample sizes in future studies may cure some of the variability exhibited.

Inclusion of the RT task during gait actually led to improvements in gait for our concussed individuals. Stride time, side-to-side CoM sway and sway peak velocity were all significantly greater for concussed individuals during level walking with the concurrent Q&A task. However, the concurrent RT task did not result in any group differences in measurements previously used to indicate instability (medial/lateral motion). Further examination of the data suggests that controls performed gait similarly between RT and Level. Rather, concussed individuals reduced their sway velocity; a potential indication of heightened alertness in comparison to their single-task performance. The effects are not believed to be a result of anticipation, as controls would have also shown improved gait parameters from level walking or improved RTs from static baselines. However, the potential increased alertness in the RT condition for the concussed group is contradicted by previous brain damaged individuals' inability to remain alert (Godefroy et al. 2002) and our own findings which demonstrated participants with grade II concussions have a similar alerting effect as controls when tested with the Atten-

tional Network Test (ANT) (van Donkelaar et al. 2005). It may be that this disparity is due to the different constraints inherent to walking versus the ANT or different task instructions as compared to Godefroy et al (2002). Further testing of alertness in our two groups is needed to support this claim.

Differences in control of CoM motion between the two groups once again appeared during the Q&A task. We hypothesize that the possible alertness to gait that concussed individuals showed during the RT task was nullified by the increased difficulty of the Q&A task. A multiple response RT or choice RT test (Bowen et al. 2001) is recommended to understand whether these effects are task related and/or difficulty related. Secondary task performance during the continuous Q&A task revealed no clear significance between groups as well. Control subjects were able to attempt slightly more answers, but not significantly more than concussed subjects. This finding may be limited by our protocol of recording only five answers attempted by the subject between the starting position and the end of walkway. It could have been the case that concussed individuals were processing all information more slowly. Significant group differences might be detected if the number of answers were recorded during a fixed time window of the gait trial.

An obvious limitation to our study was that the Q&A task was not performed as a single task, so we had no comparison for the secondary task. It has been reported that answers attempted could decrease from single to dual-task (Ebersbach et al. 1995). However, our concussed individuals were assessed with a single-task cognitive test (ANT) in our parallel studies (van Donkelaar et al. 2005, 2006; Halterman et al. 2006) and were reported with deficiencies in orienting and executive functioning. A decrease in executive functioning for concussed subjects can lead to a decreased ability to orient attention in space during a motor/cognitive dual-task situation (van Donkelaar et al. 2006). Inability to properly confine the CoM motion during gait while performing the Q&A dual-task simultaneously after a concussion might be directly correlated to a decrease in processing capacity of attention. However, it might also possibly be due to an increase in required locomotor information processing (Haggard et al. 2000). Either way, information processing capacity seems to be reduced following a concussion.

Several concepts of attentional processing state that processing capacity is limited and that when two or more tasks are performed simultaneously, the desired outcomes will occur so long as maximum capacity has not been reached (Kahneman 1973). The bottleneck concept further states that if capacity is reached, then

performance will decline on some, or all, of the tasks (Pashler 1990). The current results show trends of following suit with this concept. Concussed individuals showed a more conservative gait with instability during Q&A, along with a trend of decreased secondary task performance.

As mentioned previously, general limitations of this current study include the heterogeneity and small sample size of the subjects. However, given the incidence of concussion in college-aged adults, it is difficult to limit our recruitment to only those subjects without any previous concussions. This could be a contributing factor to the large variability in some parameters. To our knowledge, previous research using subjects with multiple concussions has failed to indicate inter-concussion durations (Mrazik et al. 2000; Bernstein 2002; McCrea et al. 2003). Nevertheless, the time period between the previous concussion and most recent (> 2 years) for our subjects is longer than any previously published reports of motor deficits (Bernstein 1999). Furthermore, a power analysis was performed using gait velocity, since it has been the most common variable reported in the literature for this patient population. Using 14 subjects in each group, our resulting analysis of power for gait velocity was 0.807, indicating our sample size was statistically adequate. Similarly, a power analysis was performed on coronal plane CoM motion (ML ROM) because of its significance in distinguishing changes in gait stability (Chou et al. 2003). This resulted in a power of 0.752, indicating a contestably adequate sample size. However, a greater sample size could still affect the group significance level of some variables. McFadyen et al. (2003) were able to demonstrate group differences following a severe TBI in all gait spatial/temporal variables. A larger sample size of concussed individuals is suspected to follow the same trend, although to a lesser degree than a severe TBI population.

Failure to measure single task performance of the Q&A task was a limitation that will be addressed in future studies to help form more support for the conclusions of attentional deficits. Measurements of the secondary task must also be modified for easier quantification. Furthermore, possibilities for measurements of different factors affected by concussion exist. Modifications to the environment that favor vestibular inputs or visual inputs can be utilized in the future to better understand the contribution of each following concussion.

Conclusions

Concussed individuals adopted a conservative gait strategy to manipulate spatial/temporal and sagittal

plane motion. However, signs of instability were still indicated by increased medial/lateral motion, supporting the idea of dysfunction in balance control. The results of this study support the possible use of gait with continual cognitive testing as a viable measurement of gait stability performance in young concussed individuals. However, a continuous variable to measure secondary task performance, such as RT during a Stroop task, will possibly serve as a better measurement of attentional deficits as compared to the limitations of the integer variable utilized in the Q&A task. A discrete simple RT test did not pose enough of a challenge to the concussed group to show the same effects, and even resulted in task-specific improvements in gait, possibly due to raising alertness. However, aspects of both tests are recommended for future design of a testing protocol for concussive deficits. Future studies will test other common secondary tasks, which are both continuously performed and able to provide a continuous resultant variable.

Acknowledgments This study was supported by the Center for Disease Control and Prevention (R49/CCR021735 and CCR023203). The authors gratefully acknowledge the assistance of Louis R. Osternig, Tonya M. Parker and Sarah R. Everman.

References

- American Academy of Neurology (1997) Practice parameter: the management of concussion in sports [summary statement]. *Neurology* 48:581–585
- Bardy BG, Laurent M (1991) Visual cues and attention demand in locomotor positioning. *Percept Mot Skills* 72:915–926
- Bell R, Hall RC (1977) The mental status examination. *Am Fam Physician* 16:145–152
- Bernstein DM (1999) Recovery from mild head injury. *Brain Inj* 13:151–172
- Bernstein DM (2002) Information processing difficulty long after self-reported concussion. *J Int Neuropsychol Soc* 8:673–682
- Bowen A, Wenman R, Mickelborough J, Foster J, Hill E, Tallis R (2001) Dual-task effects of talking while walking on velocity and balance following a stroke. *Age ageing* 30:319–323
- Brown LA, Shumway-Cook A, Woollacott MH (1999) Attentional demands and postural recovery: the effects of aging. *J Gerontol* 54A:M165–M171
- Brukner P, Kahn K (2001) *Clinical sports medicine*. McGraw-Hill, Sydney
- CDC (1997) Sports-related recurrent brain injuries—United States. *MMWR* 46:224–227
- Chou L-S, Kaufman KR, Hahn ME, Brey RH (2003) Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. *Gait Posture* 18:125–133
- Chou L-S, Kaufman KR, Walker-Rabatin AE, Brey RH, Basford JR (2004) Dynamic instability during obstacle crossing following traumatic brain injury. *Gait Posture* 20:245–254
- Cock J, Fordham C, Cockburn J, Haggard P (2003) Who knows best? Awareness of divided attention difficulty in a neurological rehabilitation setting. *Brain Inj* 17:561–574

- Collins MW, Lovell MR, McKeag DB (1999) Current issues in managing sports-related concussion. *J Am Med Assoc* 282:2283–2285
- de Jong R (1995) Perception-action coupling and S-R compatibility. *Acta Psychologica* 90:287–299
- Ebersbach G, Dimitrijevic MR, Poewe W (1995) Influence of concurrent tasks on gait: a dual-task approach. *Percept Mot Skills* 81:107–113
- Gagnon I, Swaine B, Friedman D, Forget R (2004) Children show decreased dynamic balance after mild traumatic brain injury. *Arch Phys Med Rehabil* 85:444–452
- Godefroy O, Lhullier-Lamy C, Rousseaux M (2002) SRT lengthening: role of an alertness deficit in frontal damaged patients. *Neuropsychologia* 40:2234–2241
- Guskiewicz KM, Weaver NL, Padua DA, Garrett WE Jr (2000) Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med* 28:643–650
- Haaland KY, Temkin N, Randahl G, Dikmen S (1994) Recovery of simple motor skills after head injury. *J Clin Exp Neuropsychol* 16:448–456
- Haggard P, Cockburn J, Cock J, Fordham C, Wade D (2000) Interference between gait and cognitive tasks in a rehabilitating neurological population. *J Neurol Neurosurg Psychiatry* 69:479–486
- Hahn ME, Chou L-S (2004) Age-related reduction in sagittal plane center of mass motion during obstacle crossing. *J Biomech* 37:837–844
- Halterman CI, Langan J, Drew A, Rodriguez E, Osternig LR, Chou LS, van Donkelaar P (2006) Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury. *Brain* 129(Pt) 3:747–753
- Kahneman D (1973) *Attention and Effort*. Prentice-Hall, Englewood Cliffs
- Kaya BK, Krebs DE, Riley PO (1998) Dynamic stability in elders: momentum control in locomotor ADL. *J Gerontol A Biol Sci Med Sci* 53:M126–134
- Krauss JK, Tränkle R, Kopp KH (1997) Posttraumatic movement disorders after moderate or mild head injury. *Mov Disord* 12:428–431
- Lajoie Y, Teasdale N, Bard C, Fleury M (1993) Attentional demands for static and dynamic equilibrium. *Exp Brain Res* 97:139–144
- Maki BE (1997) Gait changes in older adults: predictors of falls or indicators of fear. *J Am Geriatr Soc* 45:313–320
- McCrea M, Guskiewicz KM, Marshall SW, Barr W, Randolph C, Cantu RC, Onate JA, Yang J, Kelly JP (2003) Acute effects and recovery time following concussion in collegiate football players: the NCAA concussion study. *JAMA* 290:2556–2563
- McFadyen BJ, Swaine B, Dumas D, Durand A (2003) Residual effects of a traumatic brain injury on locomotor capacity: a first study of spatiotemporal patterns during unobstructed and obstructed walking. *J Head Trauma Rehabil* 18:512–525
- Mrazik M, Ferrara MS, Peterson CL, Elliott RE, Courson RW, Clanton MD, Hynd GW (2000) Injury severity and neuropsychological and balance outcomes of four college athletes. *Brain Inj* 14:921–931
- Parker TM, Osternig LR, Lee H-J, van Donkelaar P, Chou L-S (2005) The effect of divided attention on gait stability following concussion. *Clin Biomech* 20:389–395
- Pashler H (1990) Do response modality effects support multiprocessor models of divided attention? *J Exp Psychol* 16:826–842
- Slobounov S, Sebastianelli W, Simon R (2002) Neurophysiological and behavioral concomitants of mild brain injury in collegiate athletes. *Clin Neurophysiol* 113:185–193
- Thurman D, Alverson C, Dunn K, Guerrero J, Sniezek J (1999) Traumatic brain injury in the United States: a public health perspective. *J Head Trauma Rehabil* 14:602–615
- Vallis LA, Patla AE (2004) Expected and unexpected head yaw movements result in different modification of gait and whole body coordination strategies. *Exp Brain Res* 157:94–110
- van Donkelaar P, Langan J, Rodriguez E, Drew A, Halterman C, Osternig LR, Chou L-S (2005) Attentional deficits in concussion. *Brain Injury* (in press)
- van Donkelaar P, Osternig LR, Chou L-S (2006) Attentional and biomechanical deficits interact after mild traumatic brain injury. *Exercise and Sport Science Review* 34 (in press)
- Weerdesteyn V, Schillings AM, van Galen GP, Duysens J (2003) Distraction affects the performance of obstacle avoidance during walking. *J Mot Behav* 35:53–63
- Winter DA (1990) *Biomechanics and Motor Control of Human Movement*. Wiley-Interscience, New York
- Woltring HJ (1986) A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. *Advances in Engineering Software* 8:104–113